

CIRCUMNUCLEAR SPIRAL ARMS AND STARBURST RINGS IN MAGNETIZED BARRED SPIRAL GALAXIES

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ABSTRACT

The Seyfert galaxy NGC 1097 has an extended neutral hydrogen disk, a companion, a prominent bar and a luminous circumnuclear starburst “ring”. Magnetic fields as revealed by nonthermal radio-continuum emissions correlate well with the optical barred spiral structure on large scales, have a gross enhancement overlapping with the optical/infrared “ring”, and show a trailing swirl around and within the “ring”. We propose a scenario of bar-excited long-trailing fast magnetohydrodynamic (MHD) density waves at the modified inner Lindblad resonance (mILR), physically identified with the outer rim of the “ring”. These sustained outgoing long-waves are bounced back by the Q_M -barrier in the form of incoming short-trailing waves. The damping of these waves deposits a *negative* angular momentum into the magnetized circumnuclear gas disk. Thus, gas materials spiral inward, bring in frozen-in magnetic flux, and accumulate inside the mILR to create a circular zone of high density and magnetic flux vulnerable to massive star formation. Depending on the wave damping efficiency, this process may simultaneously sustain a net mass inflow across the “ring” and toward the nucleus. A wavelet analysis on a *Hubble Space Telescope* image of central NGC 1097 shows a distinct two-arm spiral structure extended down to the nucleus as a strong evidence for circumnuclear MHD density waves. We predict that magnetic-field observations with improved sensitivity and resolution would reveal a specific correspondence between circumnuclear optical and magnetic field spirals much as those known to exist on large scales in nearby spiral galaxies, including NGC 1097.

Subject headings: accretion, accretion disks — magnetohydrodynamics — galaxies: NGC 1097 — galaxies: spiral — galaxies: starburst — ISM: clouds

1. INTRODUCTION

In barred spiral galaxies, luminous circumnuclear rings of star bursts (Buta 1986; Telesco 1988; Barth et al. 1995) commonly appear. Some galaxies with active nuclei (AGNs) are also known to contain circumnuclear starburst rings (Simkin et al. 1980; Arsenault 1989; Barth et al. 1995). The origin of such circumnuclear activities, monitored in a wide spectrum including optical, infrared and radio-continuum bands etc, remains to be understood. (Lynden-Bell 1969; Shlosman et al. 1990). Even in the absence of self-gravity and magnetic field, numerical simulations (Piner et al. 1995) have produced gross features of circumnuclear rings in a fixed bar-potential. While the driven flux of angular momentum is independent of the details of the disk modeling, the exclusion of density waves that involve self-gravity will however affect the removal efficiency of disk angular momentum and the absence of magnetic field would at least make the formation of *massive* stars in the circumnuclear “ring” unlikely (Shu et al. 1987; Elmegreen 1994). In this Letter, we advance a physical scenario for bar- or satellite-excited *fast magnetohydrodynamic (MHD) density waves* (FMDW) in a magnetized self-gravitating disk (Fan & Lou 1996; Lou & Fan 1998; Lou et al. 2001) at the modified inner Lindblad resonance (mILR) to illustrate the processes of spiral FMDW prop-

agation, angular momentum transfer, forming circumnuclear rings, and wave-induced net mass accretions across the ring and toward the nucleus, and to comprehend optical, CO, H_I, infrared and radio-continuum observations of the barred spiral galaxy NGC 1097 in dynamic, morphologic, and diagnostic contexts (Rickard 1975; Meaburn et al. 1981; Ondrechen & van der Hulst 1983; Hummel et al. 1987; Gerin et al. 1988; Ondrechen et al. 1989; Barth et al. 1995; Beck et al. 1999; Kotilainen et al. 2000; Emsellem et al. 2001). While we focus on NGC 1097, the scenario is generally applicable to circumnuclear spirals and starburst rings in magnetized barred spiral galaxies (e.g., NGC 6951, NGC 2997 etc.). This conceptual framework also bears broad implications to accretions and MHD processes in other astrophysical disk systems such as a protostellar disk system.

With a *high* stellar velocity dispersion ($\gtrsim 100 \text{ km s}^{-1}$) and a *low* gas temperature, the central circumnuclear region of a spiral galaxy contains a thin stable¹ gas disk within a few kiloparsecs (kpc). The gas rotation curve in an extended radial range is determined by the *total* mass distribution in the galaxy (Meaburn et al. 1981; Blackman 1981; Gerin et al. 1988; Ondrechen et al. 1989) and the *background* magnetic field in the circumnuclear disk plane of a strength \gtrsim several tens of μG (Beck et al. 1999)

¹ Stability against bar-type instabilities is meant. Starbursts involve gravitational collapses on subscales along an accumulated circular zone.

² It is an idealization to posit a purely azimuthal background magnetic field, based on which we perform analysis for spiral MHD density waves.

is taken to be axisymmetric and azimuthal² to avoid the magnetic-field winding dilemma (Roberts & Yuan 1970). This circumnuclear magnetized gas disk is embedded with molecular clouds (Gerin et al. 1988) with a mean-free path l_c and a velocity dispersion v_c . When disturbed, spiral FMDWs involve collectively the magnetized gas disk embedded with clouds. The large-scale *barred spiral structure outside* the central gas disk rotates at a pattern speed Ω_p and gives rise to a time-dependent *external* periodic gravitational potential ϕ^E as felt by the central magnetized gas disk. In cylindrical coordinates (r, θ, z) , our theory is developed using the standard two-dimensional equations for coplanar MHD density waves in the central magnetized gas sheet (Lou & Fan 1998) at $z = 0$ with ϕ^E varying slowly in r as an *inhomogeneous driving term* (Goldreich & Tremaine 1978a,b; Yuan & Cheng 1991).

2. KEY RESULTS OF THEORETICAL ANALYSES

Without such ϕ^E driving and away from the resonances, the dispersion relation for *free* FMDWs in the WKBJ or tight-winding regime (Shu 1970; Fan & Lou 1996) is

$$(\omega - m\Omega)^2 \approx \kappa^2 + k^2(C_A^2 + C_S^2 + v_c^2 - 2\pi G\mu_0/|k|), \quad (1)$$

where v_c^2 mimics an “effective pressure” due to random cloud velocities, ω is the angular frequency in an inertial frame of reference, $m \geq 0$ an integer for the number of spiral arms, Ω the disk angular speed, $\kappa \equiv [(2\Omega/r)d(r^2\Omega)/dr]^{1/2}$ the epicyclic frequency, G the gravitational constant, μ_0 the background surface mass density, k the radial wavenumber, C_S the sound speed, and C_A the Alfvén speed (Lou & Fan 1998). The corresponding FMDW amplitude equation (Fan & Lou 1999) is

$$\frac{d}{dr} \left[\frac{r\mu_0 k}{(\omega - m\Omega)^2} \left(C_S^2 + v_c^2 + C_A^2 - \frac{\pi G\mu_0}{|k|} \right) |\tilde{v}_r|^2 \right] = 0, \quad (2)$$

where $\tilde{v}_r(r)$ is the magnitude of the radial velocity v_r . Equation (1) is quadratic in $|k|$ and contains the familiar short- and long-branches of FMDWs (Lou & Fan 1998). For FMDWs, it follows that $B_\theta\mu \cong \mu_0 b_\theta$, where μ is the surface mass density perturbation, and b_θ and B_θ are the perturbation and background azimuthal magnetic fields; the enhancements of μ and b_θ are therefore in phase.

The stability against *axisymmetric* ring fragmentation requires the MHD version of Toomre’s Q parameter $Q_M \equiv \kappa(C_A^2 + C_S^2 + v_c^2)^{1/2}/(\pi G\mu_0) > 1$ in a magnetized self-gravitating gas disk (Lou & Fan 1998). The radial group velocity of FMDWs is

$$F_G = -\frac{\partial\omega}{\partial k} \cong -\frac{\text{sgn}(k)[(C_A^2 + C_S^2 + v_c^2)|k| - \pi G\mu_0]}{(\omega - m\Omega)}, \quad (3)$$

with $F_G > 0$ and $F_G < 0$ for outward and inward propagations. By our sign convention, $k > 0$ and $k < 0$ represent leading and trailing spirals. Inside corotation of FMDWs, a wave packet travels away from the disk center for long-trailing and short-leading FMDWs; a wave packet travels toward the disk center for long-leading and short-trailing FMDWs. Outside corotation of FMDWs, the moving directions of wave packet reverse for all these FMDW types.

The angular momentum flux carried by a FMDW is

$$\mathcal{F}_J = -\frac{\pi m k r \mu_0}{(\omega - m\Omega)^2} \left(C_S^2 + v_c^2 + C_A^2 - \frac{\pi G\mu_0}{|k|} \right) |\tilde{v}_r|^2, \quad (4)$$

In the circumnuclear domain under consideration, observed magnetic field deviations are significant. The results of a perturbation analysis is only indicative. The effectiveness of this approach may be questionable in the fully nonlinear realm.

with the surface densities of angular momentum $\mathcal{J}^F \equiv m\mu_0|\tilde{v}_r|^2/[2(\omega - m\Omega)]$, of energy $\mathcal{E}^F = \omega\mathcal{J}^F/m$ and of wave action $\mathcal{N}^F = \mathcal{J}^F/m$. Inside and outside corotation, \mathcal{J}^F is negative and positive, respectively. By (2) and (4), the angular momentum flux of free FMDWs is conserved. The corotation at $\omega - m\Omega(r_c) = 0$ is forbidden to wave access by the Q_M -barrier when $Q_M \gtrsim 1$, and in the WKBJ regime, the *slightly* modified Lindblad resonances occur at $\Gamma \equiv \kappa^2 - (\omega - m\Omega)^2 + m^2 C_A^2 f(r)/r^2 = 0$ with $f(r) \sim \mathcal{O}(1)$ being a dimensionless analytic expression. Outside the Q_M -barrier, long-FMDWs exist *only* within the two modified Lindblad resonances, while short-FMDWs propagate within *and* outside the two modified Lindblad resonances as in the hydrodynamic case (Goldreich & Tremaine 1978a).

By a massive bar, a satellite, or a large-scale spiral structure, an external potential $\phi^E(r, \theta, t)$ felt at the central gas disk excites FMDWs at the modified Lindblad resonances r_M . Around r_M , one may write $x \equiv (r - r_M)/r_M$ and $\Gamma \equiv \mathcal{G}_M x$ with $\text{sgn } \mathcal{G}_M = \pm 1$ for *modified inner and outer Lindblad resonances* (mILR and mOLR). In the WKBJ regime, the set of *inhomogeneous* FMDW equations for small x may be reduced to the familiar form in terms of the disk self-gravity potential ϕ as

$$\frac{d^2\phi}{dx^2} - i\alpha_M \frac{d\phi}{dx} - \beta_M x\phi = i\alpha_M \Psi, \quad (5)$$

where $\alpha_M \equiv -[2\pi G\mu_0 r/(C_S^2 + v_c^2 + C_A^2)]_{r_M} \text{sgn}(k)$, $\beta_M \equiv [r^2 \mathcal{G}_M/(C_S^2 + v_c^2 + C_A^2)]_{r_M}$, and $\Psi \equiv d\phi^E/dx + 2m\Omega\phi^E/(m\Omega - \omega)$. The solutions of (5) involving Airy functions with proper energy flow directions are known; the physics of these solutions studied previously (without magnetic field) in contexts of exciting large-scale galactic density waves (Goldreich & Tremaine 1978b; Yuan & Kuo 1997) and of planetary rings (Goldreich & Tremaine 1978a, 1982) may be extended and applied to a circumnuclear magnetized gas disk. By (5), the magnitude of a FMDW is proportional to the strength of Ψ that involves ϕ^E .

By solutions of (5), long-trailing FMDWs are dominantly excited by ϕ^E at mILR and mOLR; these waves exist *between* the two resonances and propagate toward corotation after their generations at mILR and mOLR. Reflections at the Q_M -barrier transform these long-trailing FMDWs to short-trailing FMDWs that travel away from corotation and continue across the mILR and mOLR if dissipations were not strong. In the case of mILR, long-trailing FMDWs sustained by ϕ^E carries a *negative* angular momentum toward corotation; a subsequent reflection at the Q_M -barrier gives rise to short-trailing FMDWs again carrying a *negative* angular momentum that may reach the disk center until being disrupted by small-scale (\lesssim a few pc) processes around the nucleus.

3. THE CIRCUMNUCLEAR SPIRAL ARMS AND STARBURST “RING” IN NGC 1097

NGC 1097 is a barred spiral galaxy with a declination of $\sim -30^\circ$ and an estimated inclination ranging from $\sim 37^\circ$

to 57° . It is of Seyfert type with an AGN known as a LINER (Barth et al. 1995) and may host a supermassive black hole (SMBH) of $\sim 2 \times 10^{10} M_\odot$ (Rickard 1975). Estimates of its distance range from 11.6 – 17 Mpc. It has a bright circumnuclear starburst “ring” with a diameter of $\sim 18''$ and a far infrared (FIR) luminosity of $\sim 3 \times 10^{10} L_\odot$ (Telesco 1988; Gerin et al. 1988), forming stars at a rate of $\sim 5 M_\odot \text{ yr}^{-1}$ (Hummel et al. 1987). The rotation curves were determined for $r \sim 4'' - 20''$, using H_α 6563Å and [NII] 6584Å (Meaburn et al. 1981; Blackman 1981) as well as CO (J=1–0) (Gerin et al. 1988), and for $r \sim 20'' - 6'$, using neutral hydrogen HI 21 cm despite a strong depletion in the bar region (Ondrechen et al. 1989). From $r \sim 10''$ to $20''$, the inferred rotation speed $V_\theta \sim 300 \text{ km s}^{-1}$ remains roughly constant. The two dark dust lanes originating around $\sim 4'' - 5''$ follow along the inner edges of the two spiral arms and extend almost continuously out to the bar (Rickard 1975) with large arm pitch angles of $\sim 50^\circ$ there. Shown in Fig. 1 is our wavelet analysis on an *HST* image of central NGC 1097 that reveals two distinct circumnuclear spiral arms extended inward to $\lesssim 1.5''$.

Synchrotron radio-continuum emissions (Ondrechen & van der Hulst 1983; Hummel et al. 1987) at 20 cm reveal that the intensity contour closely follows the dust lanes along the bar and merges into the central circular region around $r \sim 30''$ to $35''$. The total radio intensity ring overlaps with the circumnuclear optical/infrared “ring” (Hummel et al. 1987; Telesco 1988), implying strong magnetic fields and profuse relativistic cosmic-ray electrons. Polarized radio emission at 22, 18, 6.2 and 3.5 cm (Beck et al. 1999) indicates that regular magnetic fields are parallel to the two dust lanes along the bar and gradually swirl into a trailing pattern in the central region. Relative to the circumnuclear “ring”, magnetic fields are inclined by $\sim 50^\circ$. Despite the limited resolution, it is already indicative that a trailing spiral magnetic-field pattern inside the “ring” continues toward the nucleus. By this evidence and our Fig. 1, it is almost certain that spiral FMDWs (Fan & Lou 1996; Lou & Fan 1998) play a significant dynamic role in the circumnuclear region of a barred spiral galaxy, and magnetic fields provide a valuable diagnostics. The fact that in the “ring” of NGC 1097, the radial and azimuthal components of magnetic field are comparable (Beck et al. 1999) means that the magnetic-field swirl pattern is not so tightly wound there. This perhaps relates to long-trailing FMDWs that are excited and sustained by ϕ^E at the mILR, and spiral FMDWs involve a *nonaxisymmetric* radial magnetic field b_r . Fig. 1a of Beck et al. (1999) with $15''$ resolution shows a central swirl with some axisymmetry, while their Fig. 2 with $6''$ resolution shows a central spiral pattern with nonaxisymmetry. The apparent central “axisymmetric swirl” of their Fig. 1a most likely results from a larger beam size. In terms of orientations along magnetic spiral arms, the tendency that magnetic field of central NGC 1097 seems to be axisymmetric instead of bisymmetric within the circumnuclear “ring”

region may be understood from the intuitive picture of distorted unaligned magnetic-field rings for FMDWs (Lou & Fan 1998) similar to that of distorted stellar orbits for density waves (Kalnajs 1973).

For NGC 1097, the mean magnetic field B_θ threads through the central thin HI gas disk embedded with H_2 molecular clouds (Gerin et al. 1988). Spiral FMDWs interact with the magnetized HI gas³ and H_2 clouds together. Random motions of H_2 clouds provide an “effective pressure” and a necessary mechanism for FMDW damping. The mILR is physically identified to be located at $r \sim 10''$ somewhat outside the radius⁴ of the circumnuclear “ring”. For $m = 2$, Ω at mILR is $2 + \sqrt{2}$ times Ω_p in a flat rotation curve, the corotation is located around $30'' \lesssim r \lesssim 35''$, and the mOLR would be around $50'' \lesssim r \lesssim 60''$. The latter two estimates are only indicative, as both stellar and magnetized gas disks are involved at larger r .

Our emphasis is on FMDW processes around the mILR. Long-trailing FMDWs are excited and sustained at the mILR by ϕ^E and propagate toward corotation. They are reflected by the Q_M -barrier around corotation and travel back toward the mILR in the form of short-trailing FMDWs. Inside corotation, both long- and short-trailing FMDWs carry *negative* angular momenta (Fan & Lou 1999). Owing to dissipation, these FMDWs damp and deposit in the disk their negative angular momentum as they travel. As the disk angular momentum is persistently reduced, disk material outside the mILR gradually spirals inward, bringing along magnetic flux meanwhile. As this process persists, disk materials (HI and H_2 etc) and magnetic flux would accumulate inside the mILR. Regions of high gas density and enhanced magnetic flux naturally favor births of bright young massive stars as well as star clusters (Elmegreen 1994); this presumably gives rise to a circumnuclear starburst “ring” just inside the mILR. Outside the mILR, the strength of a long-trailing FMDW should be stronger than that of a returning short-trailing FMDW owing to wave damping.

For order-of-magnitude estimates, we take $v_c \sim 35 \text{ km s}^{-1}$ (Gerin et al. 1988)⁵ and $l_c \sim 100 \text{ pc}$. The gross turbulent dissipation coefficient ν_c would be $\nu_c \sim v_c l_c / 3 \cong 3 \times 10^{26} \text{ cm}^2 \text{ s}^{-1}$. For a magnetic field of $B \sim 40 \mu\text{G}$ (Beck et al. 1999), a HI gas column density of $\lesssim 10^{21} \text{ cm}^{-2}$ (Ondrechen et al. 1989), a H_2 gas column density $\sigma_0 \sim 6 \times 10^{22} \text{ cm}^{-2}$ (Gerin et al. 1988) and a disk thickness $h \lesssim 100 \text{ pc}$, the Alfvén speed is $C_A \sim 4 \times 10^5 \text{ cm s}^{-1}$. For a gas temperature $T \lesssim 100 \text{ K}^\circ$, the sound speed is $C_S \lesssim 10^5 \text{ cm s}^{-1}$. A rule of thumb for active star formation in a magnetized gas disk is $2\pi G^{1/2} \Sigma / B \gtrsim 1$ with Σ being the surface mass density (Shu 2001, private communications). Given the above parameters, $2\pi G^{1/2} \Sigma / B \sim 8$. The Q_M estimate is uncertain, as the corotation region $30'' \lesssim r \lesssim 35''$ for two-armed spiral FMDWs may involve both stellar and magnetized gas disks; we take $Q_M \gtrsim 1$. Right at the mILR ($r \sim 10''$), the

³ A partial ionization and sufficiently frequent collisions between neutral HI gas and charged particles are presumed here.

⁴ For the Cassini division in the Saturn ring system (Goldreich & Tremaine 1978a), particles outside the Mimas’ 2:1 ILR have been cleared by density waves over 5 billion years. In the disk region outside the circumnuclear starburst ring of a barred spiral galaxy, there may be some mechanisms in operation to replenish the gas disk to avoid an outright gap.

⁵ There seems to be no escape for a high Mach number of molecular clouds in the gas disk. Resonance processes might continuously convert FMDW energy into random cloud motions.

short wavelength is $\lambda_S = (C_A^2 + C_S^2 + v_c^2)/(G\mu_0) \sim 300$ pc, while the long wavelength λ_L would be infinite; at the reflection point of the Q_M -barrier ($r \sim 30''$), they become equal $\lambda_S = \lambda_L = 2(C_A^2 + C_S^2 + v_c^2)/(G\mu_0) \sim 600$ pc. For a mean radial wave lengthscale of $\lambda_M \sim 450$ pc, the damping timescale would be $\tau_c \sim \lambda_M^2/\nu_c \cong 6 \times 10^{15}$ s. The timescale τ_w for a FMDW to go from the mILR to Q_M -barrier and back to the mILR is estimated to be $\tau_w \sim 3 \times 10^{15}$ s. Thus, a sizable fraction of negative angular momentum carried by long-trailing FMDWs excited and sustained at the mILR would have been deposited in the gas disk as a weaker short-trailing FMDW returns to the mILR. As the disk angular momentum is reduced, gas materials with frozen-in magnetic flux from outside tend to accumulate just inside the mILR to form a circumnuclear starburst “ring”. An estimate of net mass inflow rate \dot{M} involves several uncertain aspects because the magnitude of excited FMDWs relates to the strength of ϕ^E and the wave damping distribution depends on the effective viscosity as well as some nonlinear effects. By taking a $|v_r| \sim 10 \text{ km s}^{-1}$ and a $|\omega - m\Omega|r \sim 30 \text{ km s}^{-1}$ in (4), an upper limit of \dot{M} may be estimated as $\dot{M} \lesssim 10 M_\odot \text{ yr}^{-1}$. For a stronger ϕ^E , nonlinear wave and damping effects may become important and this upper limit may be raised.

superposed with the stronger long-trailing FMDW. If one were to regard the large magnetic-field pitch angle as a non-frozen-in steady state, which we think unlikely, then the upper limit of \dot{M} would be $\sim 1 M_\odot \text{ yr}^{-1}$ (Beck et al. 1999). The upper limit for \dot{M} induced by turbulent viscosity with a flat rotation curve is of the order of $\sim 1 M_\odot \text{ yr}^{-1}$. Some simulations also show that viscous torques are negligible with respect to gravitational torques several kpc away from the nucleus, when a relatively strong bar or tidal interaction is present (Combes 1991). In terms of feeding active star formation, the relative importance of viscous and gravitational torques around circumnuclear rings remain unresolved.

In our scenario, the effectiveness of wave damping holds the key for different outcomes. For a weak damping, FMDWs excited at the mILR eventually travel to the nucleus. For a strong wave damping, disk angular momentum is reduced primarily *outside* the mILR. For an intermediate wave damping, in addition to a circumnuclear “ring” formation at the mILR, remnant short-trailing FMDWs also travel *across* the mILR and be partially enhanced by the geometric converging effect (Montenegro et al. 1999). Damping of these remnant short-trailing FMDWs inside the “ring” would induce a net accretion of gas and magnetic flux to fuel nucleus activities. For NGC 1097, in addition to the starburst “ring”, circumnuclear tight-winding trailing spiral arms of FMDWs are detected (Fig. 1) down to the immediate environs of the nucleus ($r \lesssim 1.5''$). We identify this spiral structure inside the “ring” (Fig. 1) as remnant short-trailing FMDWs and suspect that the damping of these FMDWs plays a key role in fueling the central SMBH on sub-kpc scales. It is highly desirable that dedicated multiwavelength observations of circumnuclear regions of spiral galaxies would provide more examples to enrich the scenario advanced here. While already indicative, it is anticipated that refined maps of polarized radio-continuum emissions would ultimately establish a more specific correspondence of spiral structures of gas density and magnetic field around and within the circumnuclear starburst “ring”, analogous to those manifest in galactic spiral structures on larger scales. We expect the total and polarized radio-continuum spiral arms to closely follow the dust lanes along the inner edges of circumnuclear optical spiral arms of NGC 1097.

FIG. 1.— A wavelet transformed and reconstructed WFPC2/HST (F555W filter) image in false color of the central spiral arms around and within the circumnuclear starburst “ring” of the barred spiral galaxy NGC 1097 showing an angular scale lower than $2''$. The large pitch angle of $\sim 50^\circ$ of optical arms (Rickard 1975) and magnetic field (Beck et al. 1999) outside the “ring” is interpreted in terms of long-trailing FMDWs sustained by ϕ^E at the mILR. As a test, it may be possible to detect a weaker short-trailing FMDW outside the “ring”

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